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Quantum bit detector

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We propose and analyze an experimental scheme of quantum nondemolition detection of monophotonic and vacuum states in a superconductive toroidal cavity by means of Rydberg atoms.

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One of the key directions of modern physics is the following challenging problem of understanding the essence of the process of quantum measurement. Of special interest in this respect are experiments with individual quantum objects. Such applications as quantum computing, quantum cryptography and quantum teleportation, which have recently been attracting increasing attention [1], have their roots in this field. Quantum measurements and particularly experiments on the interaction of individual atoms and ions with the quantum field in a cavity are usually associated with the optical domain. With the development of the Rydberg atom technique, however, impressive results have been obtained in the microwave region [2]. This technique allows preparation and nondestructive (quantum nondemolition) repetitive measurements of Fock states with a small number of quanta in a high-Q superconductive cavity [3, 4].

In 1994 Braginsky and Khalili [5] proposed an elegant scheme employing Rydberg atoms which allowed nondestructive detection of vacuum and monophotonic states. The idea of the experiment is to use a cavity with a geometry such that the flying atom can interact twice with the field. A composite resonator comprising two sandwiched coaxial leucosapphire disks with whispering gallery modes was proposed initially with the atoms flying inbetween near the surfaces of the disks along their diameter. If the atom's velocity and the geometry are chosen such that the interaction time takes one half of the Rabi cycle, then the atom and the field may effectively exchange photons with a probability close to 100%. Dual interaction ensures that an atom leaves the cavity unexcited in both cases, when the cavity is in vacuum and one-photon state. The only difference is the state of the atom in the central area of the cavity between the two interactions. It was suggested initially [5] that an inhomogeneous d.c. field be applied in this region. This electric field detects states nondestructively (state-dependent deflection). A simpler scheme for realizing nondestructive state detection was proposed later [6], and we discuss here a practical scheme for a quantum nondemolition (QND) quantum bit detector (QBD), based on the initial idea [5] with a toroidal superconductive cavity instead of sapphire disks.

The scheme of the proposed experiment is given in Fig.1. A Rydberg atom prepared in a particular state

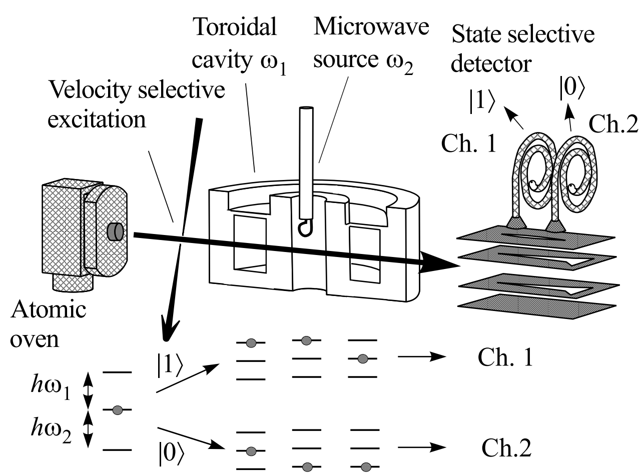

Fig.1. Scheme of the quantum bit detector. The cavity is shown in section

enters the toroidal superconductive cavity. If initially the cavity is in the vacuum state of the photon field $|0\rangle$, the state of the atom does not change in the first interaction region and the central RF field (resonant with auxiliary transition) lowers the atom state to the auxiliary lowest level. If, however, the initial state of the cavity is the one-photon state $|1\rangle$, the atom absorbs the cavity photon. To provide 100% absorption of the photon the interaction time has to be equal to one half of the Rabi cycle ($\bar{g}L/v = \pi/2$, where $\bar{g}$ is the effective Rabi frequency, L is the interaction length and v is the velocity

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of the atom). When the atom is in the upper state, the central field is not resonant and the state is unchanged. During the second interaction the atom returns the photon back to the cavity. In this way the information about the cavity quantum state is recorded in the atomic state and the quantum state of the cavity is not destroyed. The information recorded in the atomic state can easily be read out by the state-selective detector based on field ionization.

The transition between $61D_{5/2}$ and $63P_{3/2}$ levels of the ^{85}Rb Rydberg states, the cavity mode (21.456 GHz) and $61D_{5/2} \to 59F_{7/2}$ (21.122 GHz) for the probe are planned to be used in the experiment.

The theory of the QBD based on the Jaynes-Cummings model and the standard master equation approach can be created in the same way as the theory of the micromaser field (see details in Refs. [7–9]). The basic difference is that atoms are prepared not in the excited but in the ground state and that interaction between the cavity and the atoms is more complicated.

The complete initial state P of the system atom in the ground state plus the cavity field can be written in the form:

$$P = \sum_{n,m} |g,n\rangle \rho_{nm} \langle g,m|. \qquad (1)$$

Three sequential interactions (the first one with quantum field in the cavity in the first interaction region, the second with intermediate classical field transforming $|g\rangle$ into the auxiliary state $|f\rangle$, which is off-resonant, and finally the third with quantum field) will transform to

$$|g,n\rangle \longrightarrow |f,n\rangle \cos(\phi\sqrt{n}) - \\ - \frac{1}{2} i|e,n-1\rangle \sin(2\phi\sqrt{n}) - |g,n\rangle \sin^2(\phi\sqrt{n}). \qquad (2)$$

This transformation is considered ideal here, though finite efficiency can also easily be accounted for. If as in micromaser theory we are interested only in the evolution of the state in the cavity, ignoring the states of the atoms, we can trace over the atom states $\rho(n) \to \to tr_{\text{atom}} P_{\text{after}}$, obtaining after some transformations

$$\rho \longrightarrow \cos^2(\phi\sqrt{n})\rho(n) + \\ + \sin^4(\phi\sqrt{n})\rho(n) + \frac{1}{4}\sin^2(2\phi\sqrt{n+1})\rho(n+1). \qquad (3)$$

The first term here states that the atom left the first interaction unexcited and was transformed to the auxiliary state, the second one that atom absorbs the photon and returns it back to the cavity, and the third is the probability of the atom leaving the cavity in excited state.

Taking into account the interaction of the cavity field with the heat-bath between atom flights [7, 8], we obtain the following master equation

$$\frac{\partial \rho}{\partial t} = -\frac{r}{4}\sin^2(2\phi\sqrt{n})\rho(n) + \gamma\bar{n}n\rho(n-1) - \\ - \gamma(\bar{n}+1)n\rho(n) + \frac{r}{4}\sin^2(\phi\sqrt{n+1})\rho(n+1) - \\ - \gamma\bar{n}(n+1)\rho(n) + \gamma(\bar{n}+1)(n+1)\rho(n+1). \qquad (4)$$

Here $\gamma = \omega/2\pi Q$ is the decay constant of the cavity, and $\bar{n} = [\exp(\hbar\omega/kT) - 1]^{-1}$ is the mean number of photons in the cavity for the thermal state at temperature T. Each of the 6 terms in the master equation corresponds to the probability of transition to or from the level n caused by the atom or heat-bath. The first three terms can be transformed to the last three terms with the replacement $n \to n+1$ and a change of sign. Taking into account that these first three terms also become zero for $n = 0$, one can easily obtain a steady-state solution for the QBD when $\partial\rho/\partial t = 0$

$$\rho_{SS}(n) = \rho_{SS}(0) \prod_{m=1}^{n} \frac{4\gamma\bar{n}m}{r\sin^2(2\phi\sqrt{m}) + 4\gamma(\bar{n}+1)m}. \qquad (5)$$

The results of numerical calculations of the mean photon number $\langle n \rangle$ and relative variance (Fano factor) $Q_f = (\langle n^2 \rangle - \langle n \rangle^2)/\langle n \rangle$ according to (5) for the set of parameters achievable in the experiment are presented in Fig.2. As is clearly seen, the QBD works as an effective cooler for the cavity field. For most of the Rabi phase values the state in the cavity is close to the vacuum state, except peaks corresponding to multiples of

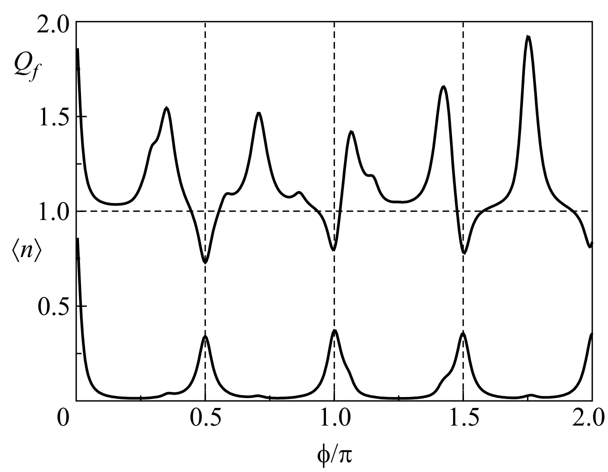

Fig.2. Dependence of steady states of e.m. field in the QBD on the Rabi phase ϕ with atom rate $r = 3000\,\text{s}^{-1}$, temperature $T = 1.4\,\text{K}$ ($\bar{n} = 0.92$) and $Q = 2 \cdot 10^9$. The lower curve is the mean number of photons $\langle n \rangle$, the upper curve is the Fano factor Q_f

$\pi/2$. For these values of the phase sub-Poissonian statistic of the field ($Q_f < 1$) is observed with minima of the Fano factor. This is the regime of the QND state selector. Large maxima of the Fano factor correspond to Rabi phase resonance for two-photon states and small maxima to three-photon states (correspondingly, $\phi = k\pi/(2\sqrt{2})$ and $\phi = k\pi/(2\sqrt{3})$.

If we now shall start monitoring the state of the atoms leaving the cavity with the velocity chosen to satisfy condition $\phi = \pi/2$, we can distinguish in a quantum-nondemolition way two lowest quantum n-states $|0\rangle$ and $|1\rangle$ - quantum bit. If dissipation in the system is absent, every new measurement of the state (every new atom) will provide the same result as the first measurement since QND measurements are repetitive and the initial state will be preserved. If the Q-factor is limited and the temperature is not zero, then due to interaction with the heat-bath the cavity can lose and acquire photons and the lifetime of n states is limited; if however the rate of atoms $r \gg \gamma$, repetitive measurements are still possible and, plotting the dependence of the atom state on the time of measurement, we'll observe characteristic steps of comparable length, corresponding to thermal transitions between the $|0\rangle$ and $|1\rangle$ states.

Fig.3 presents the results of a Monte-Carlo simulation of this possible experiment.

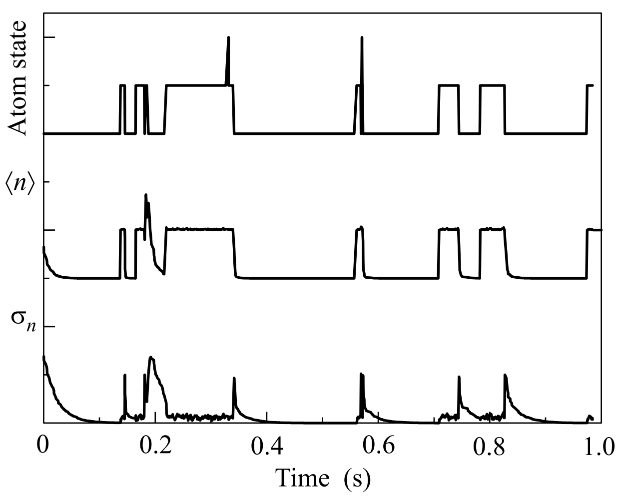

Fig.3. Simulation of quantum bit detection regime at $\phi = \pi/2$. The parameters used in the calculations are the same as in Fig.2. The upper curve is the state of the atoms detected, the central curve is the mean number of photons in the cavity $\langle n\rangle$, the lower curve is the standard deviation of the QBD $\sigma_n = \sqrt{\langle n^2\rangle - \langle n\rangle^2}$

Toroidal cavities with the $TE(001)$ mode were found to be most suitable for the experiment. The lines of electric field are wrapped around the center, vanishing on the cavity walls. The mode provides good atom–field coupling (Rabi frequency 47 kHz) and has axial symmetry avoiding difficulties with mode orientation. The geometrical factor of the cavity is $\Gamma = 408\,\Omega$. Several cavities made of pure niobium (99.9%) were manufactured and tested. The cavities comprised two parts, a cup and a cover, welded by electron beam welding, chemically etched and baked in ultra high vacuum at 1800 °C. The cover has a membrane for tuning the resonant frequency by mechanical and piezo squeezing. The internal dimensions of the cavities are as follows: inner diameter – 21 mm; outer diameter – 38 mm; height – 12.7 mm. The cavities were tested at temperature 1.4 K and a Q-factor $2 \cdot 10^9$ was observed. These obtained parameters were used in the theoretical calculations and simulations of the previous section. The measured frequency intervals for mechanical adjustment of the cavities (10 MHz) and piezo fine tuning (250 KHz) are appropriate for the achieved precision of cavity manufacturing.

The experimental setup for the QBD in general is similar to that described in Refs. [2, 9] and consists of a pumped ^{4}He cryostat (achievable $T = 1.3$ K) and laser system. A beam of Rb atoms is produced in an atomic oven connected to the cryostat. The cavity and tuning mechanism are fixed to the coldfinger attached directly to the helium bath of the cryostat. The state-selective atom detector, mounted a few centimeters behind the resonator, allows atoms to be detected atoms either in the ground and excited states or in the auxiliary and ground states. It consists of an electrostatic system creating gradient ionizing field and two channeltron electron detectors [2, 3].

The laser system for preparing the Rydberg excited state is based on a cw ring dye laser and external stabilized intracavity frequency doubler with UV power output about 15 mW at wavelength of 297 nm of. Since the experiment requires a defined interaction time, Doppler velocity selective excitation is employed with the laser beam inclined at an angle of about 11° to the normal angle. The laser frequency is stabilized on the same Rydberg transition using an auxiliary chamber with atomic beam.

To prepare atoms in the ground state, required for the final QBD experiment, the same laser setup can be used with the addition of an auxiliary Stark field to allow forbidden $5^2S_{1/2} \to 61^2D_{5/2}$ transitions.

In preliminary experiments the beam of Rydberg atoms in the excited state was guided through the cavity and detected. Count rates up to 30,000 atoms/sec were measured.

To sum up, the parameters already achieved in the experiment open the possibility of demonstrating repetitive QND detection of vacuum and single-photon states of a microwave field.

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